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## DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

## AERONAUTICAL RESEARCH LABORATORY

MELBOURNE, VICTORIA



Flight Mechanics Technical Memorandum 437

# F-111C FLIGHT DYNAMIC MODEL AERODYNAMIC DATA-BASE DEVELOPMENT AND VERIFICATION

by

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## SUMMARY

*A description is given of the process used to develop and verify the aerodynamic data-base of the F-111C flight dynamic computer model. The process uses stability and control derivatives obtained from flight trials performed at the RAAF's Aircraft Research and Development Unit (ARDU). Model response has been verified against aircraft time histories measured during the trials. The results presented compare the aircraft response in lateral manoeuvres, at various wing sweeps. A very good degree of matching is possible, although further investigation should correct inaccuracies which can cause poor estimation of yaw rate.*

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# CONTENTS

## Nomenclature

| | |
|---|---|
| $\alpha$ | angle of attack |
| $\beta$ | angle of sideslip |
| $\theta$ | pitch angle |
| $\phi$ | roll angle |
| $\Lambda$ | wing sweep |
| $p$ | roll rate |
| $q$ | pitch rate |
| $r$ | yaw rate |
| $C_l$ | rolling moment derivative |
| $C_n$ | yawing moment derivative |
| $C_y$ | sideforce derivative |
| $\delta a$ | aileron deflection |
| $\delta r$ | rudder deflection |
| $\delta sp$ | spoiler deflection |
| $C_{l_{\delta a}}$ | rolling moment derivative due to aileron deflection |
| FYS | sideforce, stability axes |
| FYW | sideforce, wind (airpath) axes |
| L | rolling moment |
| N | yawing moment |
| $rmass$ | reciprocal of aircraft mass |
| $vtas$ | velocity (true air speed) |

# 1 Introduction

A six degree of freedom flight dynamic model of the F-111C aircraft has been developed at the Aeronautical Research Laboratory (ARL) to support aircraft operations and aircraft and weapon system development (Reference 1). The model has been developed from the manufacturers design reports and wind-tunnel reports for the F-111A version. A series of flight trials was performed on the the F-111C at the RAAF's Aircraft Research and Development Unit (ARDU) to obtain stability and control derivatives for validation of the ARL model.

Analysis of the data was conducted by the Aircraft Flight Dynamics Group at ARL using the parameter estimation techniques described in Reference 2. Results from the analysis are reported in References 3 to 8. Small disturbance models of the aircraft longitudinal and lateral aerodynamic characteristics are used in the identification process to determine the aerodynamic parameters. These parameters are then used to modify the aerodynamic data base in the ARL six degree of freedom non-linear flight dynamic model.

Modifications have been made to the ARL flight dynamic model to facilitate this updating process, often referred to as model validation. The process is a necessary part of flight dynamic model development but is not rigorously defined and so relies, to a degree, on engineering judgement. The objective with the F-111C model is to combine the modified aerodynamic data base with the existing model of the flight control system to give a good representation of the measured flight behaviour.

The purpose of this report is to document this process and to present preliminary results. Control inputs measured during the flight trials were used to drive the flight dynamic model and comparisons were made between the time histories generated by the model and those measured in flight. This report describes the approach used for the lateral directional aerodynamic parameters and describes the evaluation of a number of lateral responses from the flight Trials. A brief investigation of the longitudinal motion is also included, which indicates that a similar approach can be used for the longitudinal parameters.

# 2 Model Description

The six degree of freedom flight dynamic model uses standard rigid body aircraft equations of motion. Quaternions are used to calculate aircraft attitudes and a fourth order Runge Kutta method is used to integrate the equations. The force equations are calculated in airpath axes and the moment equations are calculated in body axes. These equations are programmed using the Advanced Continuous Simulation Language (ACSL) see Ref. 9. and are described in detail in Ref. 10.

The aerodynamic database contains the stability and control derivatives that allow calculation of forces and moments acting on the aircraft due to its own motion and to control surface deflections.

## 3 Procedures for Verifying the Lateral Derivatives

The lateral response of an aircraft may be assessed by inspection of the response variables: roll rate $p$, yaw rate $r$, and angle of sideslip $\beta$. In verifying the influence of the lateral derivatives, the calculated responses of these variables to measured control inputs have been compared with the measured response.

The derivatives which influence the lateral directional response are contained in the following force and moment equations which are used in the flight dynamic model.

Sideforce Equation

$$FYS = C_{y_p}p + C_{y_r}r + C_{y_\beta}\beta + C_{y_{\delta a}}\delta a + C_{y_{\delta r}}\delta r + C_{y_{\delta sp}}\delta sp + weight \times \sin\phi\cos\theta \tag{1}$$

Rolling Moment Equation

$$L = C_{l_p}p + C_{l_r}r + C_{l_\beta}\beta + C_{l_{\delta a}}\delta a + C_{l_{\delta r}}\delta r + C_{l_{\delta sp}}\delta sp \tag{2}$$

Yawing Moment Equation

$$N = C_{n_p}p + C_{n_r}r + C_{n_\beta}\beta + C_{n_{\delta a}}\delta a + C_{n_{\delta r}}\delta r + C_{n_{\delta sp}}\delta sp \tag{3}$$

These total forces and moments are substituted into the flight dynamic model and the state equations are integrated to produce the output responses in roll, yaw and sideslip.

Because of coupling between all three equations it is a complex problem to isolate the source of any errors. For example, if the calculated rolling moment is poorly matched, and is traced to an incorrect value for the roll due to yaw, this could be due to an error in either the value of the derivative $C_{l_r}$ or due to errors in the response variable $r$.

Some means of isolating the calculation of the three motions $p$, $r$, and $\beta$ was considered desirable, so that each equation could be analysed separately, using flight measured values for $p$, $r$ and $\beta$.

This has been organised in the ACSL simulation programme by using three logical switches called BEBM (Beta Equals Beta Measured) PEPM, and RERM for $p$ and $r$ respectively. By setting any two of these switches to .TRUE., and the third to .FALSE., the equations are calculated using the actual measured values of the first two variables, and the computed value for the third.

Further examination of the full six degree of freedom equations of motion reveals that there can also be significant coupling from the longitudinal motion into the lateral response. Two additional logic switches have therefore been added for alpha and q, these are: AEAM and QEQM.

Thus by setting RERM=.T. and BEBM=.T., but PEPM=.F., in addition to AEAM=.T. and QEQM=.T., the roll rate $p$ will be calculated using measured values of $r$, $\beta$, $\alpha$, and $q$, and so the $C_l$ derivatives can be checked without errors caused by incorrect calculation of these parameters affecting the accuracy of the calculated roll rate.

When flight measured data is not used, the logical flag FLTDAT is set to FALSE. Thus, having verified the $C_n$, $C_l$, $C_y$ derivatives using selected measured responses, the model can then be run with all three variables calculated simultaneously.

The procedure adopted to verify the derivatives is as follows:

1. Run the *ACSL* model using database values.
2. Run model using Flight Trial values with AEAM=.T. QEQM=.T. and:
   (a) PEPM=.F. RERM=.T. BEBM=.T., observe accuracy of $p$
   (b) PEPM=.T. RERM=.F. BEBM=.T., observe accuracy of $r$
   (c) PEPM=.T. RERM=.T. BEBM=.F., observe accuracy of $\beta$
   (d) Run with PEPM,RERM,BEBM=.F., so p,r, and $\beta$ are all calculated simultaneously.

Coupling from the longitudinal motion into the lateral directional response can occur in two ways. Firstly, the lateral aerodynamic data are stored in the model in derivative form as functions of the Mach no., altitude, and the longitudinal variable, angle of attack. Secondly, for manoeuvres with large rates of yaw and particularly roll, the sideforce equation includes a significant inertial contribution which is a function of angle of attack. The first contribution is generally small unless the longitudinal variables are grossly in error, however the second contribution can be large.

For the Airpath system of axes used in the F-111C ACSL programme the sideforce equation can be arranged as follows:

$$\dot{\beta} = FYW \times rmass/vtas - RSB \tag{4}$$

where
$$\begin{aligned} FYW &= FYS\cos(\beta) - FXS\sin(\beta) \\ FXS &= (xthrust + weight\ \sin(\theta))\cos(\alpha) \\ &\quad +(zthrust + weight\ \cos(\theta))\sin(\alpha) - drag \\ FYS &= C_{y_r}r + C_{y_p}p + C_{y_\beta}\beta + C_{y_{\delta a}}\delta a + C_{y_{\delta r}}\delta r + C_{y_{\delta sp}}\delta sp + \\ &\quad weight \times \sin\phi\cos\theta \end{aligned}$$
and
$$RSB = p\sin(\alpha) + r\cos(\alpha)$$

FXS is the force in the X direction which is calculated from the longitudinal equations, and FYS is the force in the Y direction and is calculated from the sideforce equation (Equation 1).

The RSB term has a very significant influence on $\dot{\beta}$ *in high roll rate manoeuvres,* and so will be sensitive to the accuracy of the predicted angle of attack $\alpha$.

The roll and yaw rates are derived from the angular accelerations $\dot{p}$ and $\dot{r}$, which are calculated from the rolling and yawing moment equations as follows:

$$\dot{p} = LC_1 + NC_2 + (pC_3 + rC_4)q \tag{5}$$

$$\dot{r} = NC_8 + LC_2 + (pC_9 - rC_3)q \tag{6}$$

where $C_x$ are inertial terms as given by:

$$
\begin{aligned}
C_0 &= I_{XX} I_{ZZ} - I_{XZ}^2 \\
C_1 &= I_{ZZ} / C_0 \\
C_2 &= I_{XZ} / C_0 \\
C_3 &= C_2 \times (I_{XX} - I_{YY} + I_{ZZ}) \\
C_4 &= C_1 \times (I_{YY} - I_{ZZ}) - (C_2 \cdot I_{XZ}) \\
C_8 &= I_{XX} / C_0 \\
C_9 &= C_8 \times (I_{XX} - I_{YY}) + (C_2 \cdot I_{XZ})
\end{aligned}
$$

It can be seen that $q$, the pitch rate, contributes gyroscopic moments. A switch QEQM is defined in the programme, which when set to .TRUE. substitutes the measured value of $q$ in these equations. Any differences between the measured and calculated roll rate $p$ or yaw rate $r$ can then be traced to either the lateral derivatives or to errors in calculation of the longitudinal motion.

# 4 Implementation of Flight Data in Flight Dynamic Model

Additional subroutines were written to enable the flight dynamic model to access the aerodynamic derivatives obtained from flight measurements.

For the verification phase it is proposed to transform the existing database values, which are based on wind-tunnel measurements, into the new values by applying a scale factor and a bias terms according to the equation:

$$C_{l,n,y NEW} = C_{l,n,y OLD} \times \text{scale factor} + \text{bias}$$

Appropriate scale factors and bias errors were calculated as part of the flight test analysis procedures. An alternative option is also provided which switches the data directly from the existing data to the new data by setting the scale factor to zero and the bias term equal to the new data.

To control this operation an ACSL logic parameter LATFDR has been defined, which if set to .TRUE. will then modify the LATeral Flight DeRivatives to the flight derived values.

With LATFDR=.TRUE. subroutine LAT.F will call LATDB.F to obtain the database values, then will call subroutine MODLATDERV.F to MODify the LATeral DERViatives. A selection of the derivatives to be modified can be made via the subroutine MODLATDERV.F. The routine reads two files, MODDERV.DAT and LATCOEFS. File LATCOEFS contains the scale factor and bias values to be applied, whilst the MODDERV.DAT file contains a list of lateral derivatives, and assigns a logic value to each derviative. Only if this logic value is equal to .TRUE. will the specific lateral derivative be modified.

Therefore, to convert from the existing data base to the flight derived data both the ACSL parameter LATFDR, and also the logic variable in the MODDERV.DAT file must be set to TRUE.

Similar procedures are provided for the longitudinal derivatives, via subroutines LONG.F, LONGDB.F, MODDERV.DAT and LONGCOEFS.

# 5 Modifications to ACSL Model

During the verification exercise, a number of corrections, changes, and enhancements were made to the ACSL model. These are summarised under the following seven different headings.

1. **Correction of errors.** When the flight trials stability and control derivatives were initialy used, poor matching resulted. After investigation, a number of errors were found in the coding, which were corrected as follows.

   (a) The database contained values of zero for the spoiler derivatives at certain spoiler deflections. The values given in the database F111LATDB.F18 for 'SPOILER'=45 at 'SWEEP'=35 & 45 were zero for the DLSP, DNSP and DYSP derivatives. This error was rectified by replacing the zero values with the values given for 'SPOILER'=26.

   (b) Negative spoiler deflections were being made positive. In program LATDB.F the spoiler deflection value SPOILERU was made an absolute value for the purpose of retrieving the values of the derivatives from the database, but these values were not then modified to the correct sign.

   (c) Limiting of the maximum alpha value was programmed incorrectly. A minor error had meant that the limiting would never occur.

   (d) Centre of gravity corrections were being carried out incorrectly. Program LAT.F calls CGLAT to apply cg corrections, however flight trial data is corrected for instrumentation offset in a flight data processing program, and so the use of CGLAT was not required for the flight trial data. When comparing model response and measured data it is essential to make the comparison at a common reference point.

   (e) The lateral derivatives were being incorrectly modified by subroutine CONLAT. This is used for certain database values in the original model development to convert F-111A data to those of an F-111C, but should not be done in the case of flight trials values.

   (f) The variable break point values for parameter MACH1 in the F111LATDB.F18 database were not being read correctly. These values are written on two lines, but the second line was not being read.

2. **Correcting Control Inputs.** To simulate lateral manoeuvres the ACSL program is driven by the control inputs aileron, spoiler, and rudder. In the initial trim condition prior to the manoeuvre the model values should all be zero, since the model trims in symmetric flight. However, in reality the measured values will have initial non-zero values as a result of aircraft asymmetries and biases in the instrumentation. This was corrected by subtracting the initial value of each control setting from the control time history records.

3. **Plotting of Derivatives.** The lateral and longitudinal aerodynamic derivatives were defined to be ACSL parameters. This allows them to be plotted as a function of time to check for discontinuities in the data tables etc.

4. **Operation of LATFDR, LONFDR.** These ACSL logic parameters are defined in the main program, and passed to the LAT.F and LONG.F subroutines. If their values are true, then MODLATDERV.F or MODLONGDERV.F are called to modify the lateral or longitudinal derivatives to flight trial values.

5. **Reading file MODDERV.DAT.** This file contains the individual logic values for the lateral and longitudinal derivatives. These values are read by MODLATDERV.F or MODLONGDERV.F, to determine which of the derivatives are to be modified to flight trial values.

6. **Reading file LATCOEFS, LONGCOEFS.** Once program MODLATDERV.F has read file MODDERV.DAT, it then reads LATCOEFS to obtain the values of the scale and bias factors. The use of external files such as MODDERV.DAT and LATCOEFS allows these values to be changed without the need to recompile and execute the program.

7. **Operation of AEAM, QEQM, PEPM, RERM, BEBM.** These are logic parameters which have been defined in the main ACSL program, and if set to .TRUE. will cause the calculated value to be replaced with the measured value.

An investigation was also made into the method used in the model for calculating spoiler deflections. During the flight trials the spoiler deflections were measured directly. When analysing flight manoeuvres these measurements are used as inputs to the ACSL model. The ACSL model also calculates a spoiler deflection from the measured lateral stick position. The model can thus use either of these sources of $\delta sp$ when simulating flight trial manoeuvres. The best roll response has been obtained using the values of $\delta sp$ calculated from the lateral stick position, which are in general higher than those which were measured directly. The cause of this discrepancy has not been identified.

## 6 Results

Comparisons are presented of the calculated response of $p$, $r$ and $\beta$, using flight trial lateral stability and control derivatives, with the measured response. Figures 1, 2, 3, 4 and 5 are shown for the wing sweep angles 72.5, 50, 35, 26 and 16 degrees respectively. The figures on the left hand side show $p$, $r$ and $\beta$ when calculated separately using measured values of the responses, whilst the figures on the right show the response for the complete model. Prior to calculating the complete model responses, some of the $C_n$ derivatives were altered to improve the models estimated response. These alterations were based on the matching of yaw rate with the other variables fixed, as shown (Fig. 6).

Results of a simulated longitudinal manoeuvre are shown (Fig. 7). In this manoeuvre however only database derivatives have been used. Again, the graphs on the left hand side show the response using measured values (for $q$, $\alpha$ and $\theta$) in sequence, whilst those on the right side show the same parameters calculated from the complete model.

Simulation of a Dutch roll manoeuvre was also performed (Fig. 8). In similar fashion to the longitudinal results, only database derivatives were used.

# 7 Discussion

## 7.1 Lateral Manoeuvres

Lateral roll manoeuvres were simulated for wing sweeps of 16, 26, 35, 50 and 72.5 degrees. Simulations were conducted using derivatives from the database, and also from flight trials data. Results are presented for cases with $p$, $r$, and $\beta$ obtained separately from flight or from computation.

For some of these cases the calculated values of $p$, $r$ and $\beta$ are very close to the measured response (Fig. 9). In these cases it can be assumed that the $C_l$, $C_n$, $C_y$ derivatives are correct, and that the ACSL programs and equations of motion correctly predicted the aircraft motion. The agreement also confirms that the lateral derivatives have been correctly estimated from the flight data.

For some cases the yaw rate response is incorrectly calculated (Fig. 10). When the three parameters $p$, $r$, and $\beta$, are calculated separately, using flight trial derivatives, the $p$ and $\beta$ response are very close to measured behaviour, whilst the yaw rate $r$, although following the same pattern as the measured yaw rate, does not attain the same values.

The exact reason for the poor accucuracy of the yaw rate has not been established. Although altering the value of the $C_{n_\beta}$ and $C_{n_{\delta r}}$ derivatives can improve the accuracy of the yaw rate, when calculated in isolation (Fig. 11), the matching deteriorates again when all three motions are calculated simultaneously (Fig. 12). The fact that changing the $C_{n_\beta}$ and $C_{n_{\delta r}}$ derivative appears to give better matching does not prove these derivatives are incorrect.

The incorrect calculation of the yaw rate also has a degrading influence on the accuracy of the other parameters, particularly sideslip $\beta$, when all three are calculated simultaneously (Fig. 13).

The incorrect yaw rate has an effect on the sideslip due to a coupling of the motions as shown by the equations used to calculate $\beta$. Whilst $C_{y_r}$ is often a dominant derivative, in terms of it's numerical value, an investigation made by altering the $C_y$ derivative has shown that *in the rapid roll manoeuvres* it has very little influence on the sideslip.

Investigations described in Section 3 have shown that in the rapid roll manoeuvres the RSB term has a major influence on the calculation of the sideslip angle. This is demonstrated graphicaly, by plotting the individual terms which combine to produce the sideslip angle. As shown in Fig. 14, the calculated $\beta$ (BETAD) is very close to the measured $\beta$ (BETAM). This calculated $\beta$ is integrated from $\dot{\beta}$ (DBETAR) which has two terms, one from the RSB component, and the other from the FYW component (Eqn. 4).

These terms are plotted (Fig. 15) and, as can be seen, the RSB term is almost identical to the negative of DBETAR, and the FYW term is very small in comparison to $\beta$. This shows that, for the lateral roll manoeuvres, $\beta$ is almost entirely caused by the RSB term and not from the FYW term.

The FYW term itself has two components, FYS and FXS, although the FXS term is very small (Fig. 16). The FYS term is calculated (Eqn. 4) from the components due to the derivatives, and a weight term, which is dominant. When the $C_y$ derivatives are set to zero, there is very little change in the value of FYS calculated (Fig. 17a), and hence no detectable difference in the $\beta$ calculated (Fig. 17b).

Since the RSB term is the dominant cause of the sideslip in the lateral manoeuvres, then when $\beta$ is calculated separately, with PEPM, RERM and AEAM=.T., then the calculated $\beta$ would be expected to be almost identical to the measured $\beta$.

Any error in the $\beta$ angle calculated simultaneously with $p$ and $r$ is due to inaccuracies in these values, and not due to any possible error of the $C_y$ derivatives, which have almost no effect for the rapid roll manoeuvres.

The incorrectly predicted yaw rate could also have an effect on the roll rate via the $C_{l_r}$ term used in calculating L and the inertial term $rC_4$ in the equation

$$\dot{p} = LC_1 + NC_2 + (pC_3 + rC_4)q$$

from which $p$ is calculated. The $LC_1$ term is dominant in calculating $\dot{p}$, since the other components $NC_2$ and $(pC_3 + rC_4)q$ are effectively zero. This is shown in (Fig. 18), where these components are denoted $LC1$, $NC2$ and $PPRQ$ respectively. This demonstrates that only the equation determining $L$ governs the motion of the roll, and that the only coupling arises from the terms within this equation. The accuracy with which the roll rate $p$ is predicted implies that the rolling moment derivatives are quite accurately estimated.

Whilst the equation used to calculate the yaw rate has a very similiar form to that used for the roll rate, the yaw rate is often poorly predicted.

The yaw rate acceleration is given by

$$\dot{r} = NC_8 + LC_2 + (pC_9 - rC_3)q$$

and Fig. 19 shows the contributions to $\dot{r}$ by each term. Unlike the behaviour of $\dot{p}$, $\dot{r}$ has contributions from all three terms and has coupling from the roll motion in three terms; firstly from $C_{n_p} \times p$ in calculating $N$; secondly from $C_{l_p} \times p$ in calculating $L$; and finally the $P \times C_9 \times q$ term.

Since the roll derivatives have been shown to be estimated with reasonable accuracy, then the poor predition of yaw rate would indicate that the yaw derivatives are not well estimated.

Once the yaw rate has caused inaccuracies in the roll and sideslip values, these incorrect parameters will then affect the yaw rate, via a feedback of the errors in the roll and sideslip. This naturally complicates the system, and makes it difficult to assertain cause and effect between parameters.

As shown in Fig. 11, altering the $C_n$ derivative changes the yaw rate response, but none of the changes introduced has resulted in a satisfactory match for this case (Fig. 12).

In some cases (Fig. 20) it was noticed that the calculated response shows a small roll in the opposite direction to the intended roll response.

This was shown to be due to the $C_{l_{\delta r}}$ term since all other roll derivatives, at this point of the manoeuvre, are acting in the correct direction, whilst the moment produced by $C_{l_{\delta r}} \times \delta r$ was the only term opposing them. Reducing the value of $C_{l_{\delta r}}$ to the database value corrected this problem (Fig. 21).

The $C_{l_{\delta r}}$ derivative may also be in error in other manoeuvres but is not detectable since for these cases the time between initiation of rudder and aileron deflection is too small to enable the response to be observed. This example shows the complexity of the verification process. The general policy in these situations is to accept the flight data, which represents an average of the results over the appropriate Mach No. range for that configuration.

### 7.2 Longitudinal Manoeuvres

An exploratory investigation of the longitudinal model was carried out using the procedures developed in the lateral verification study. The longitudinal comparisons shown in Fig. 7 were obtained using derivatives from the database and have not been adjusted to reflect flight trials results. However it can be seen that the calculated values of $q$, $\alpha$, and $\theta$ match up reasonably well with the measured responses.

Using a similar procedure to the lateral analysis, the longitudinal simulations were conducted, with the variables PEPM, RERM and BEBM set to TRUE. Although the equations for calculating $q$, $\alpha$, and $\theta$ include coupling from the lateral motion in $p$, $r$ and $\beta$, these terms are generally small. However, the facility has been provided to enable measured lateral quantities to be used if required.

Correct matching between the calculated and measured $\alpha$ will depend on the requirement that the model trimmed $\alpha$, at the start of the simulation, is the same as the measured trimmed $\alpha$ at the start of the manoeuvre. Part of the verification process will be to establish a matching of the trim conditions.

### 7.3 Dutch Roll Manoeuvre

The estimated behaviour of the aircraft in a Dutch roll is presented in Fig. 8, which shows reasonable accuracy for $p$ and $\beta$ when they are calculated in isolation. Unfortunately, when all three variables are predicted, the frequency of the model behaviour is no longer accurate. These preliminary results were obtained using F-111C database values. Better reults should be achieved when lateral derivatives from the flight trials are used, although attempts to use these in the Dutch roll have not been successful yet.

## 8 Conclusion

Procedures for updating the ARL F-111C flight dynamic model with flight data have been developed. These procedures have been applied to a number of lateral manoeuvres for wing sweeps of 72.5 to 16 degrees. The comparison of model predictions with flight measurements of lateral response reveal the following characteristics.

- A very good degree of matching between the model calculated values of $p$, $r$ and $\beta$ and the measured values is possible.
- For some cases the yaw rate $r$ is poorly estimated. This is believed to be due to inaccurate $C_n$ derivatives.
- When the yaw rate is inaccurate, the accuracy of the calculated sideslip angle $\beta$ is significantly reduced, whilst the accuracy of the roll rate $p$ is affected only to a minor degree.
- The $C_{l_{\delta_r}}$ derivative is often over-estimated, which degrades the accuracy of the calculated roll response.
- Strong coupling exists in the sideforce equation arising from resolving roll inertia terms into the airpath axes. Errors in the calculation of angle of attack can lead to incorrect resolution of these inertia terms.

Results of a preliminary investigation of a longitudinal manoeuvre have been presented. These results show that the wind-tunnel data for the longitudinal aerodynamic parameters is much more accurate than the lateral data. Hence smaller adjustments to the data will be needed.

Further investigation into the calculation of the yaw rate to determine the suspected inaccurate $C_n$ derivatives, is recommended.

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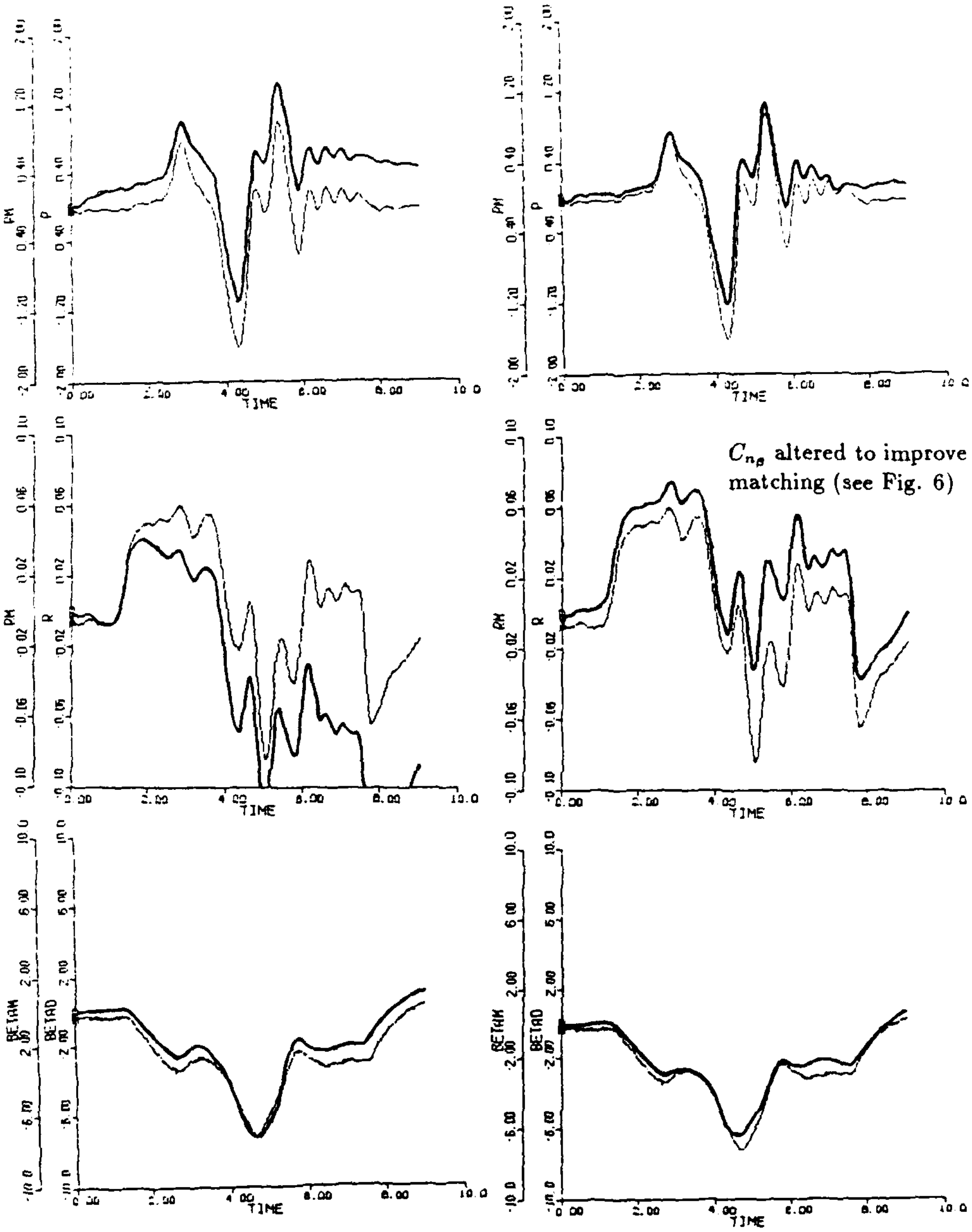
LATERAL MANOEUVRE, $\Lambda = 72.5°$

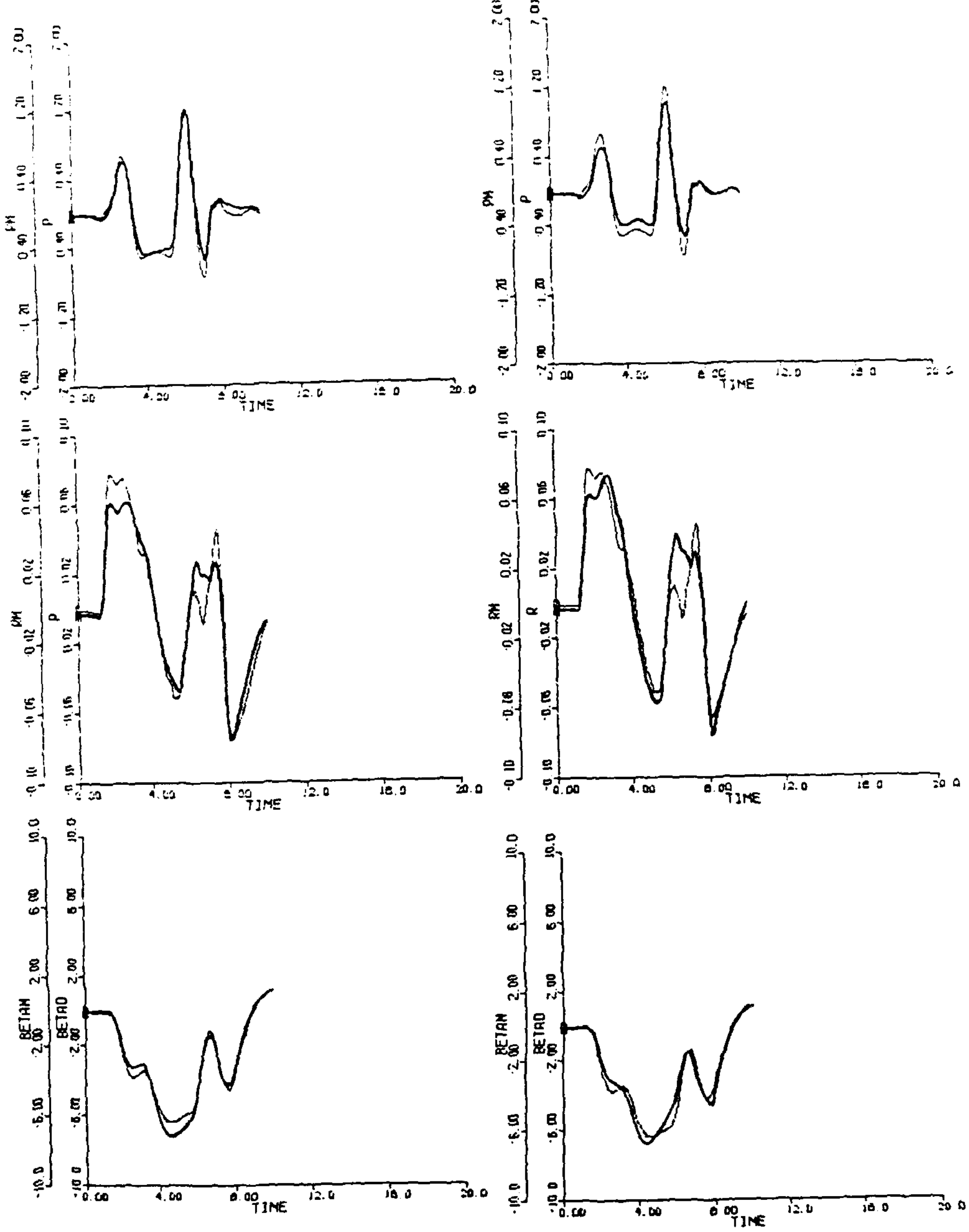



$p, r, \beta$ calculated seperately $\qquad$ $p, r, \beta$ calculated simultaneously

—— measured data
**——** calculated data

**Fig. 1 Comparison of measured and calculated data of a lateral manoeuvre, $\Lambda = 72.5°$, using Flight Trials derivatives.**

LATERAL MANOEUVRE, $\Lambda = 50°$




$p, r, \beta$ calculated seperately

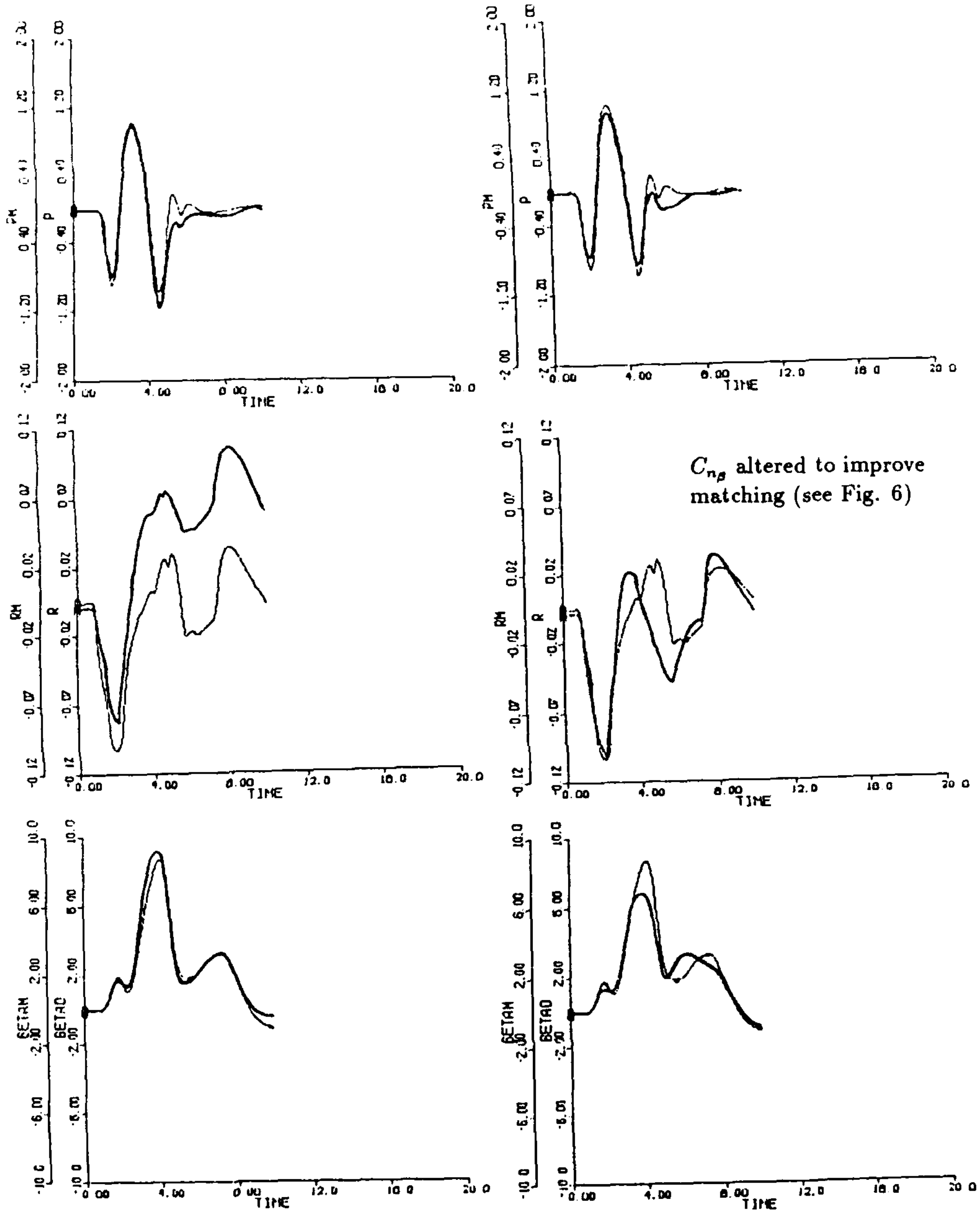
$p, r, \beta$ calculated simultaneously

——- measured data

—— calculated data

**Fig. 2** Comparison of measured and calculated data of a lateral manoeuvre, $\Lambda = 50°$, using Flight Trials derivatives.

LATERAL MANOEUVRE, $\Lambda = 35°$




$p, r, \beta$ calculated seperately

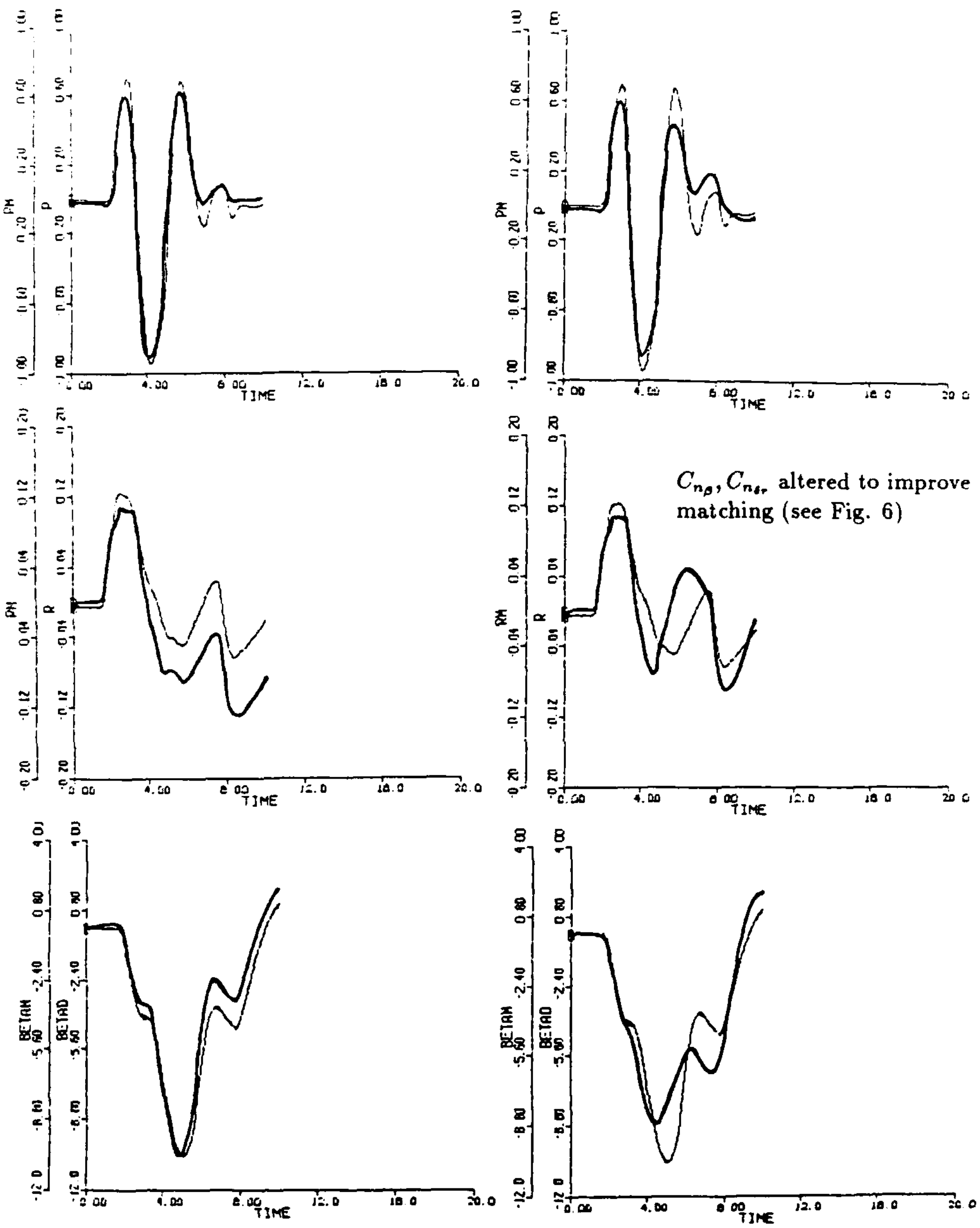
$p, r, \beta$ calculated simultaneously

——- measured data

—— calculated data

**Fig. 3** Comparison of measured and calculated data of a lateral manoeuvre, $\Lambda = 35°$, using Flight Trials derivatives.

LATERAL MANOEUVRE, $\Lambda = 26°$




$p, r, \beta$ calculated seperately

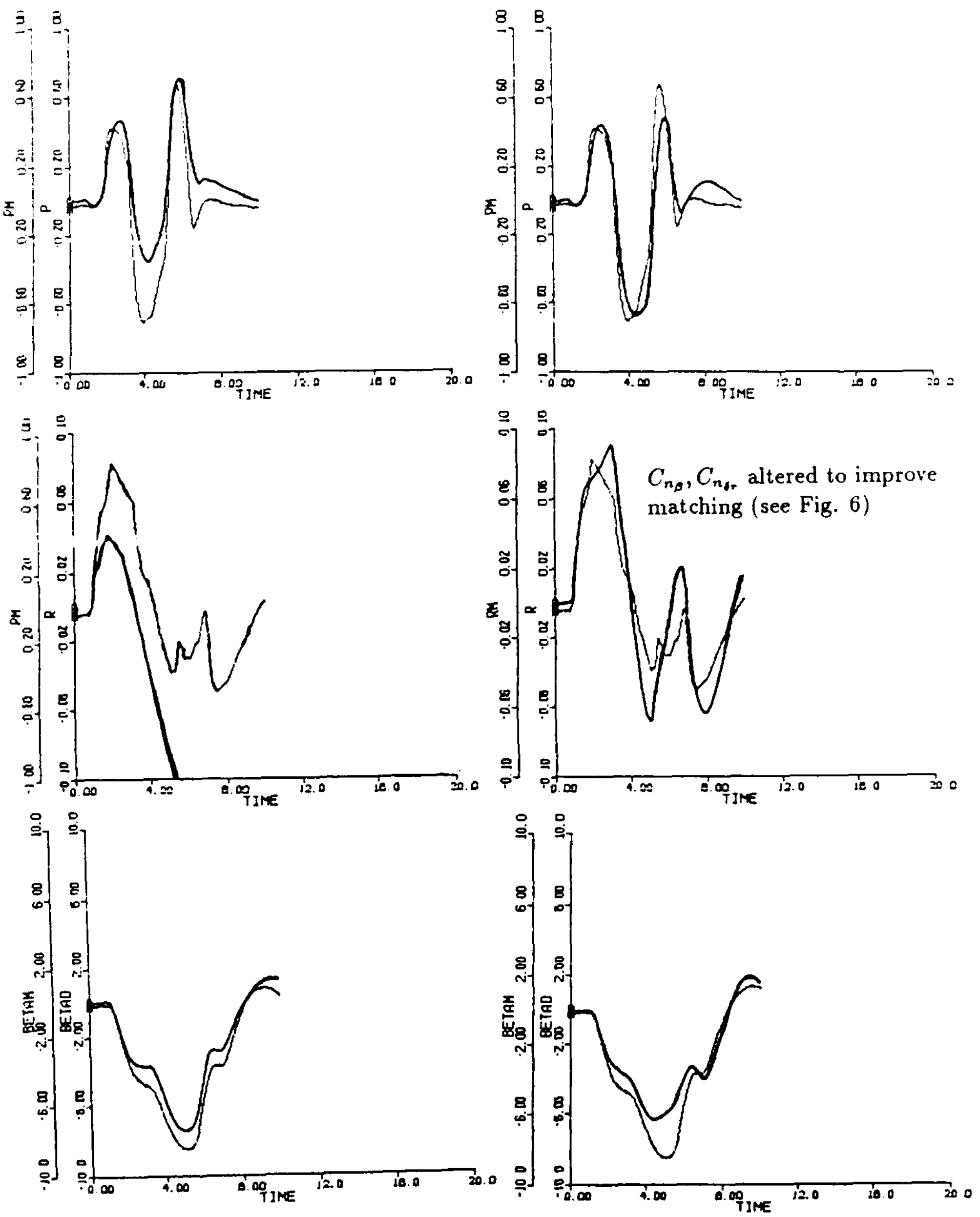
$p, r, \beta$ calculated simultaneously

—— measured data

**——** calculated data

**Fig. 4** Comparison of measured and calculated data of a lateral manoeuvre, $\Lambda = 26°$, using Flight Trials derivatives.

LATERAL MANOEUVRE, $\Lambda = 16°$




$p, r, \beta$ calculated seperately

$p, r, \beta$ calculated simultaneously

——- measured data

—— calculated data

**Fig. 5** Comparison of measured and calculated data of a lateral manoeuvre, $\Lambda = 16°$, using Flight Trials derivatives.

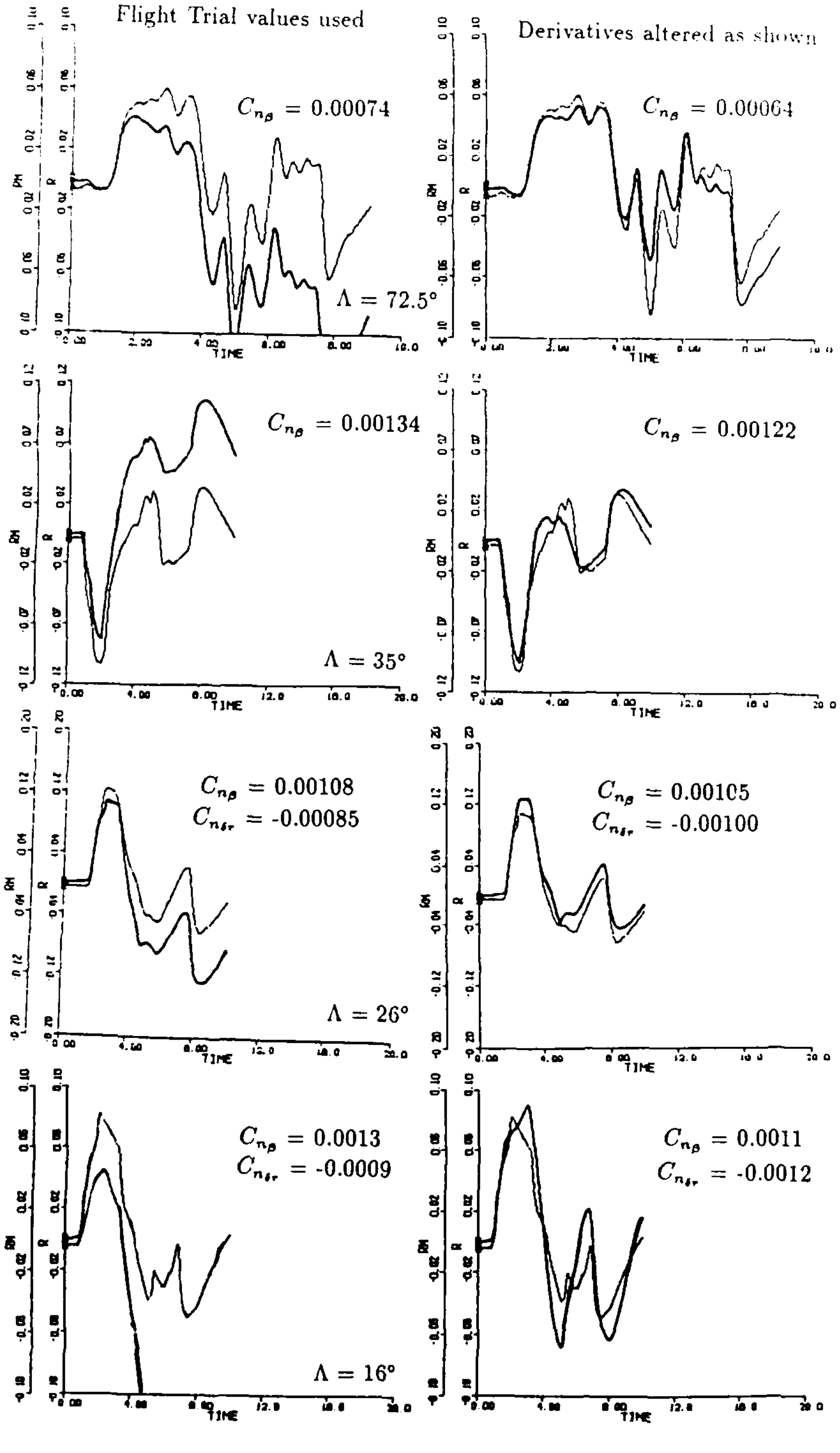
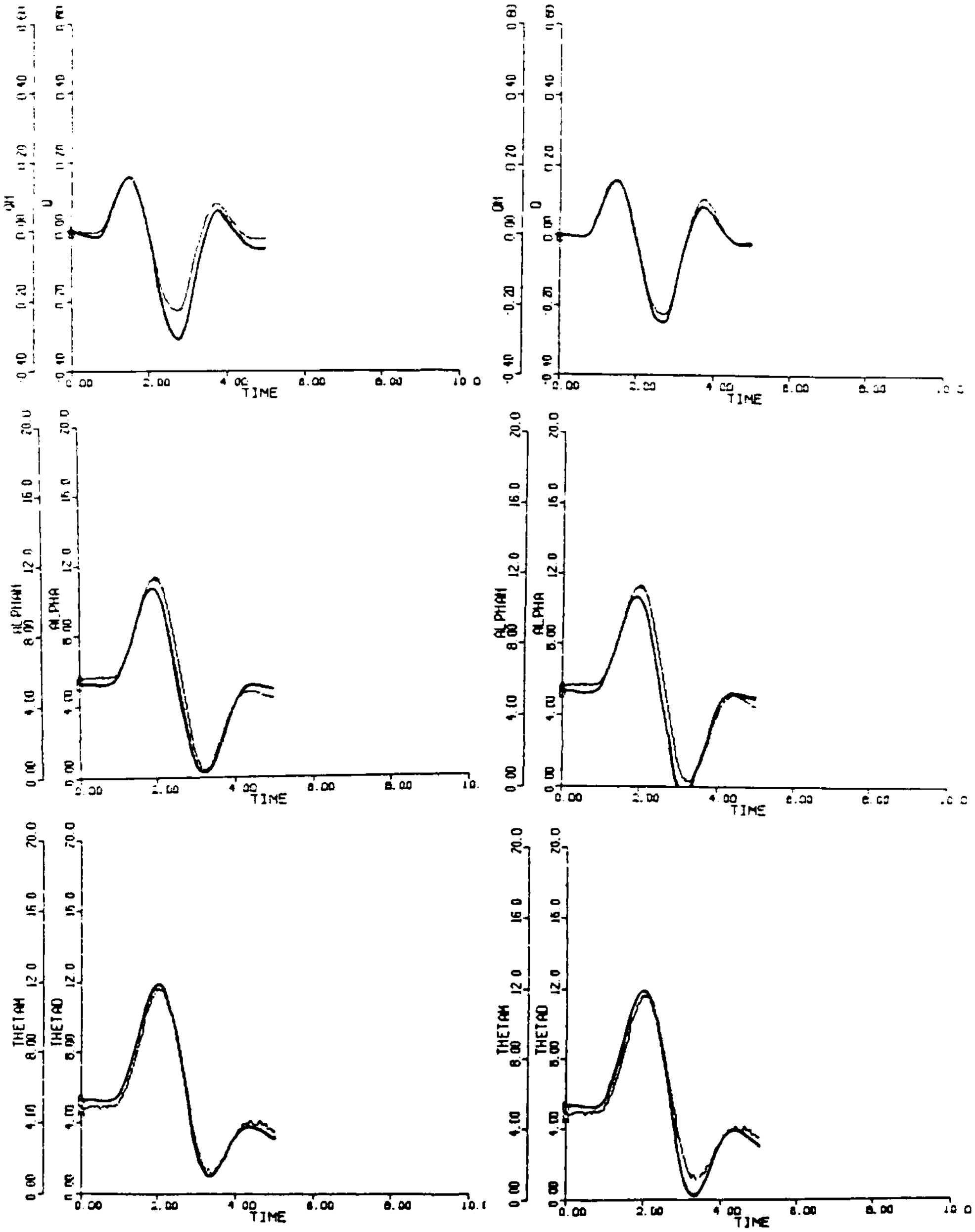



**Fig. 6** Improvement in calculation of $r$ (seperately from other variables) due to altering $C_n$ derivatives.

LONGITUDINAL MANOEUVRE, $\Lambda = 16°$



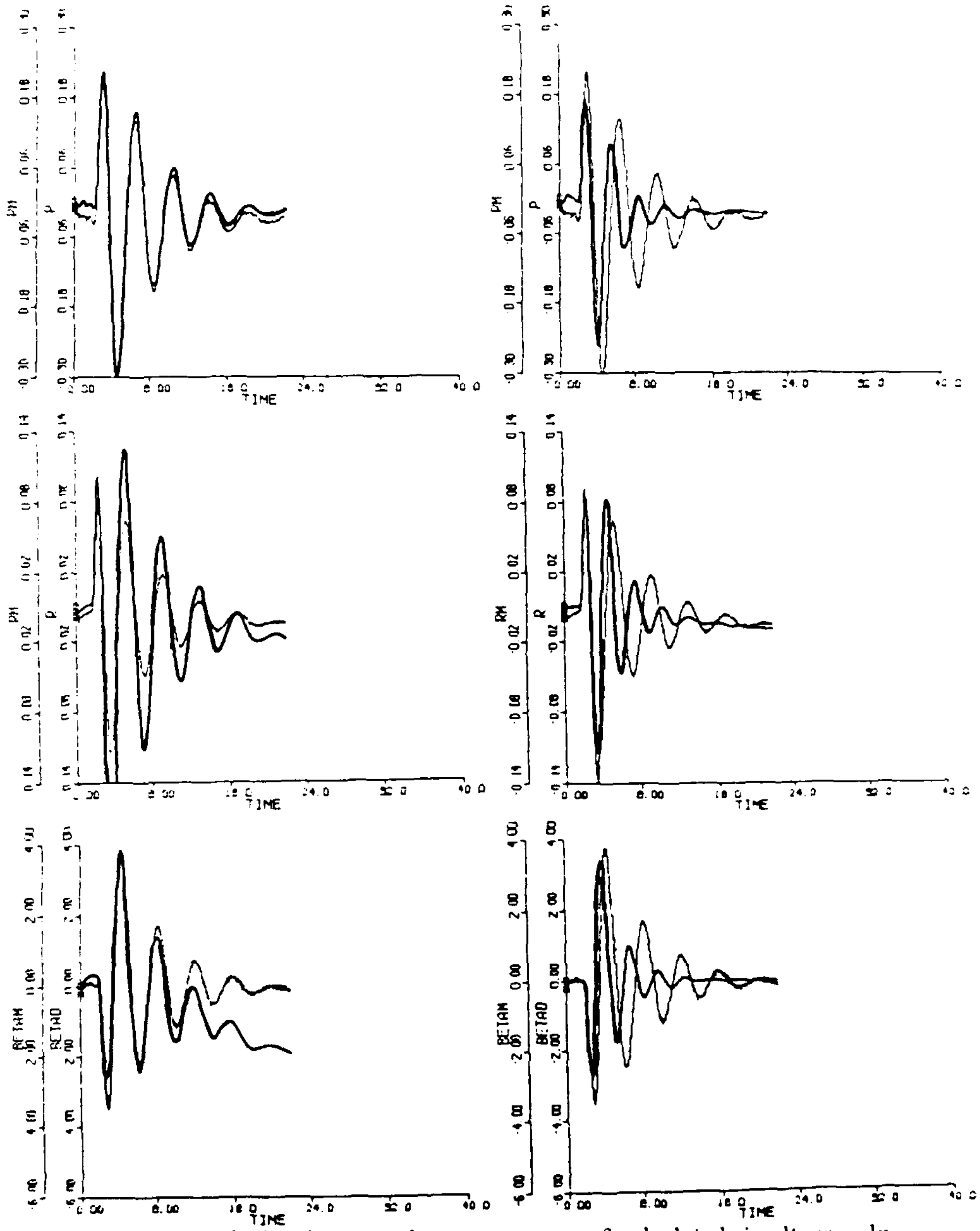

$q, \alpha, \theta$ calculated seperately

$q, \alpha, \theta$ calculated simultaneously

- measured data
- calculated data

**Fig. 7** Comparison of measured and calculated data of a lonitudinal manoeuvre, $\Lambda = 16°$, using Database derivatives.

DUTCH ROLL MANOEUVRE, $\Lambda = 26°$



$p, r, \beta$ calculated seperately

$p, r, \beta$ calculated simultaneously

—— measured data

▬▬ calculated data

**Fig. 8** Comparison of measured and calculated data of a Dutch Roll manoeuvre, $\Lambda = 26°$, using Database derivatives.

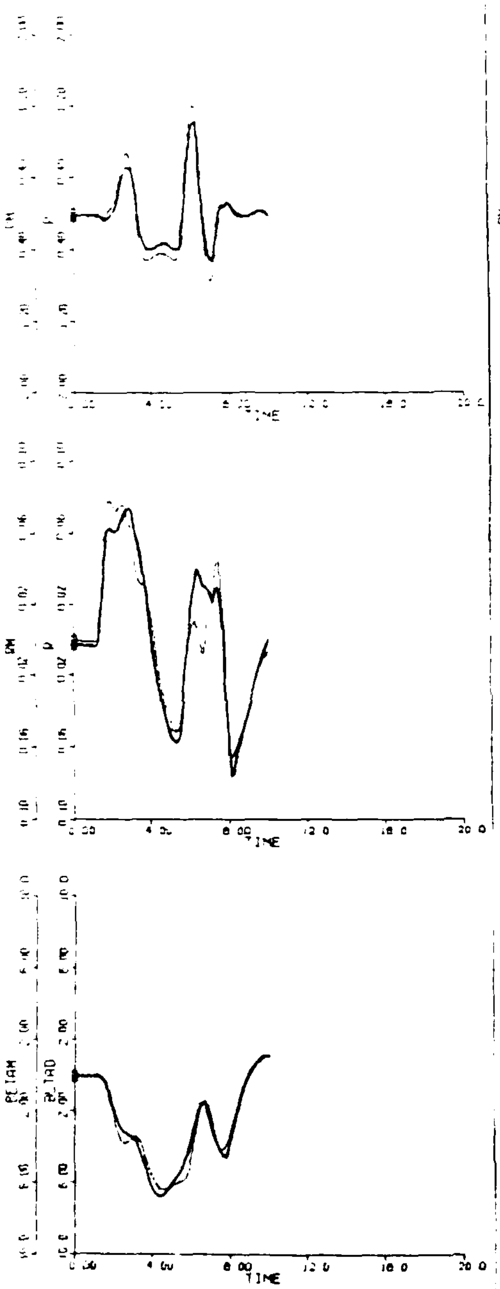


**Fig. 9** Example of close matching of measured and calculated $p, r, \beta$ variables calculated simultaneously. (Results for $\Lambda = 50°$)

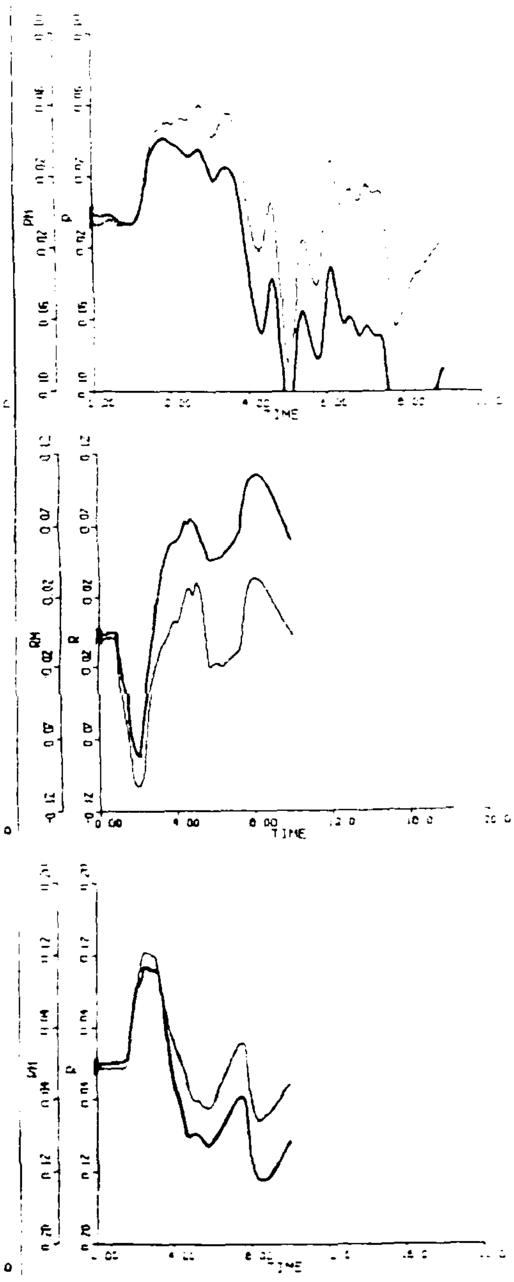


**Fig. 10** Inaccurate estimation of yaw rate. (Results for $\Lambda = 72.5, 35, \&26°$).

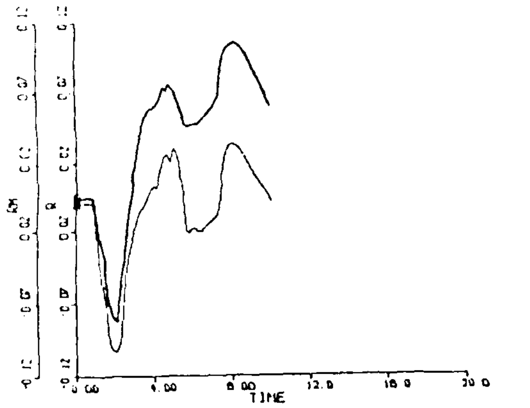



Fig. 11a Yaw rate calculated seperately with all $C_n$ values equal to flight trials results.

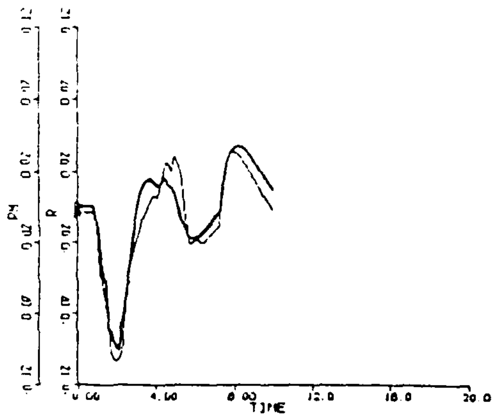



Fig. 11b Yaw rate calculated seperately with $C_{n_\beta}, C_{n_{\delta r}}$ altered.

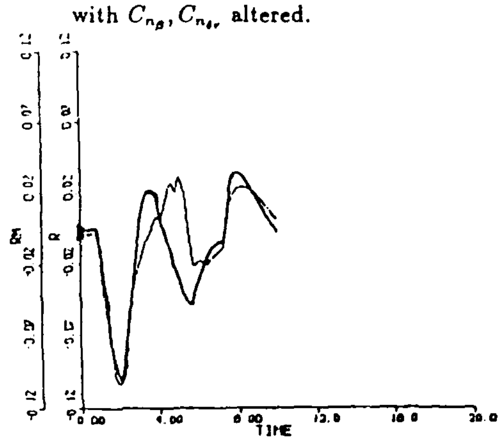



Fig. 12 Yaw rate calculated simultaneously with $C_{n_\beta}, C_{n_{\delta r}}$ altered as in Fig. 11b

—— calculated data

—— measured data

Results for $\Lambda = 35°$ lateral manoeuvre

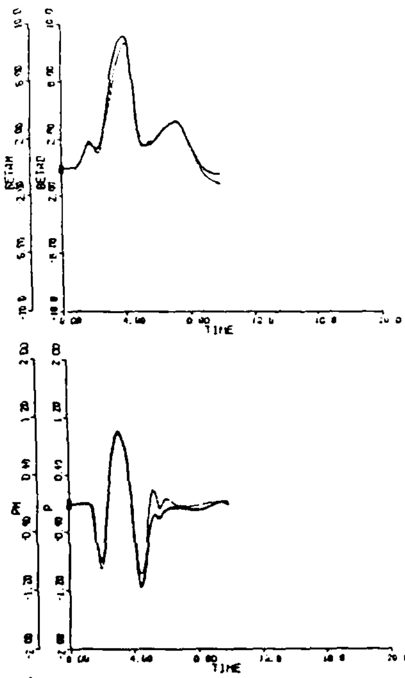



Fig. 13a $\beta, p$ calculated simultaneously with correct yaw rate as input.

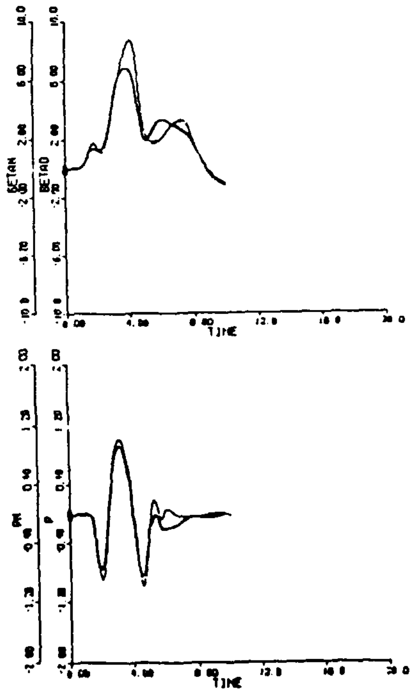



Fig. 13b $\beta, p$ calculated simultaneously with calculated yaw rate (shown in Fig. 12) as input.

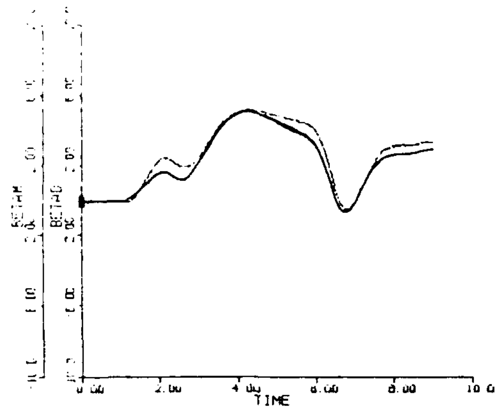



Fig. 14 Calculated and measured $\beta$ with $C_y$ derivatives equal to flight trial values.

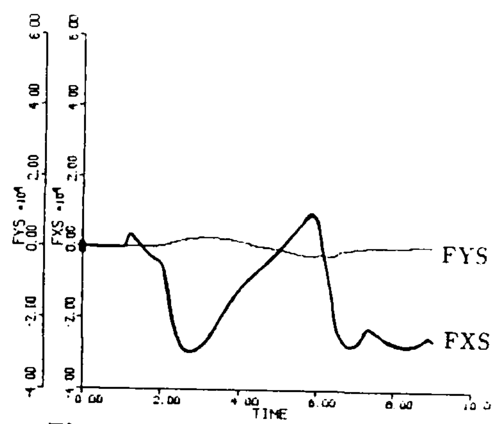



Fig. 16 FYS term with $C_y$ derivatives equal to flight trial values.

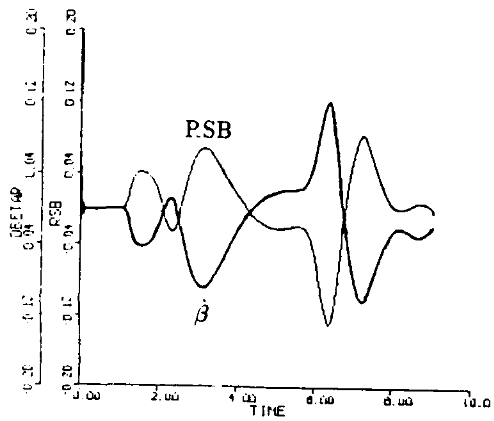



Fig. 15a Comparison of $\dot{\beta}$ and RSB terms.

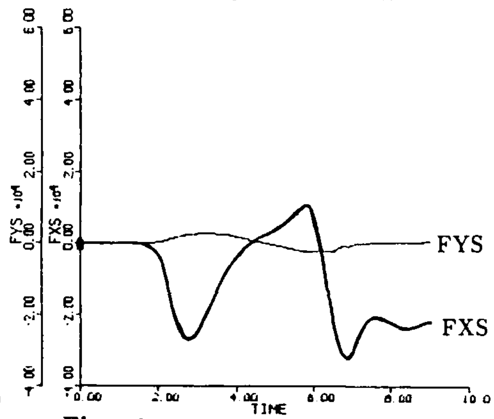



Fig. 17a FYS term with all $C_y$ derivatives equal to zero.

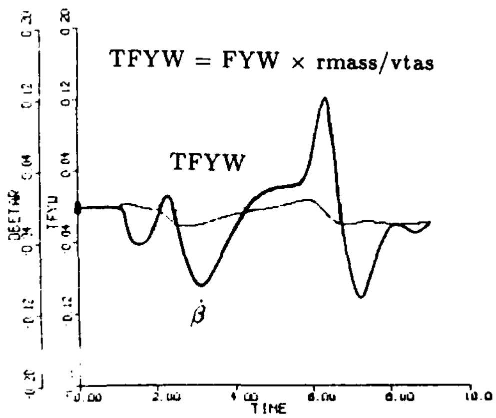



Fig. 15b Comparison of $\dot{\beta}$ and TFYW terms.

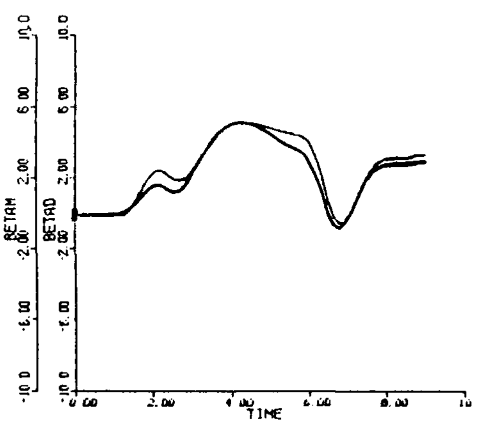



Fig. 17b Calculated and measured $\beta$ with $C_y$ derivatives zero. (Compare to Fig. 14)

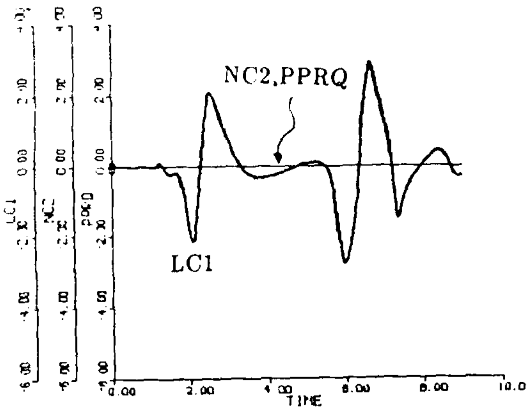



**Fig. 18** Comparison of magnitude of terms.

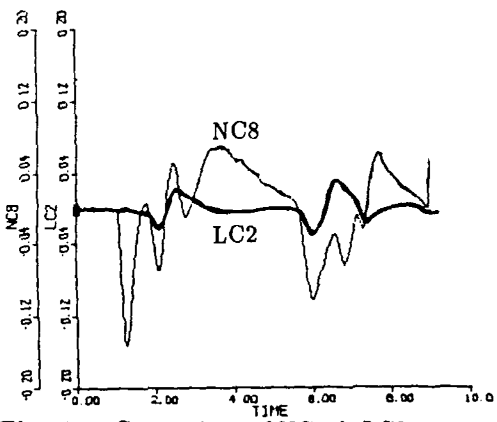



**Fig. 19a** Comparison of NC8 & LC2 terms used to calculate $\dot{r}$.

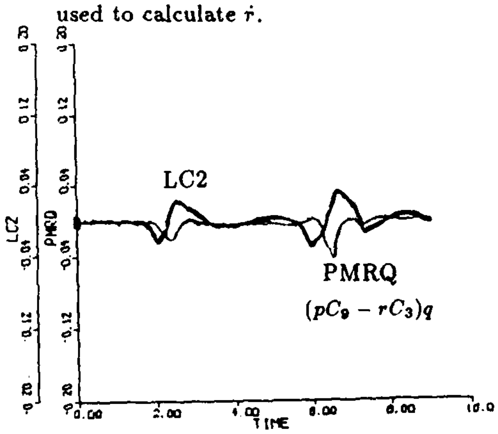



**Fig. 19b** Comparison of LC2 & PMRQ terms used to calculate $\dot{r}$.

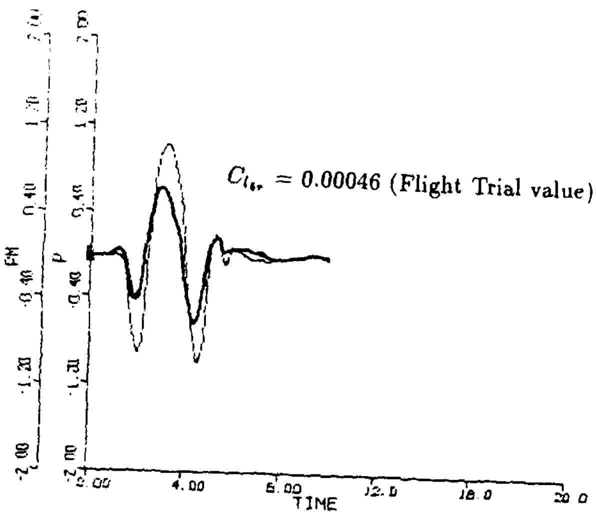



**Fig. 20** Calculated roll rate with overestimated $C_{l_{\delta r}}$ value.

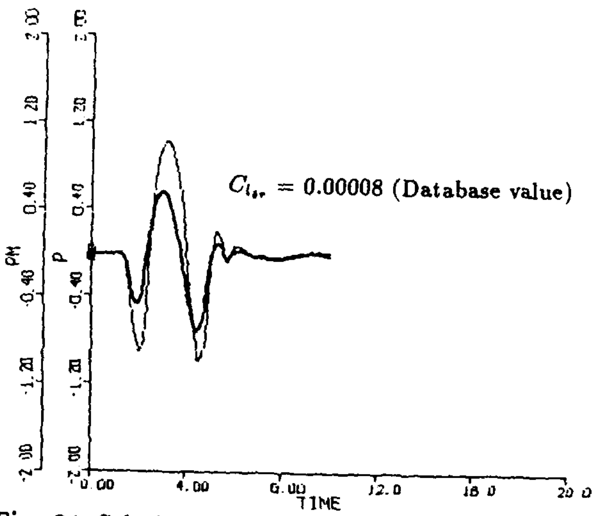



**Fig. 21** Calculated roll rate with reduced $C_{l_{\delta r}}$ value.

—— calculated data
------ measured data

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